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1 UNITARY METAL STRUCTURAL MEMBER WITH INTERNAL  
2 REINFORCEMENT

3  
4  
5 CLAIM FOR PRIORITY

6 This application claims the benefit of U.S. Provisional Application  
7 No. 60/255,242, filed December 13, 2000, under 35 U.S.C. §119.

8  
9 FIELD OF THE INVENTION

10 The present invention relates generally to structural members.

11 BACKGROUND OF THE INVENTION

12 Metal structural members have a wide-ranging applicability as  
13 components in various types of structural frames. The members may be used, for  
14 example, in aircrafts and automobiles to form a structural frame. The members  
15 might also find applicability in building construction and consumer devices.  
16 Another potential application is in spacecraft. The members are typically  
17 elongated components. A critical property for structural members is strength to  
18 weight ratio. Weight is an obvious drawback in many applications, just as  
19 strength is an obvious advantage.

20 Conventional structural metal members are composed of rolled or  
21 extruded components with constant cross-sectional size and shape, and a constant  
22 wall thickness. Typically, the cross-section of a member is circular so that the  
23 overall shape of the support member is cylindrical. However, the member may

1 have a rectilinear cross-section. Generally, the strength to weight ratio in these  
2 types of members is a function of the material and the wall thickness, which might  
3 be thick enough to form a substantially solid member in some instances or a  
4 substantially hollow member in other instances.

5 Selection or design of a particular component with a specific wall  
6 thickness and cross-sectional geometry is determined by the maximum loads and  
7 stresses a particular portion or portions of that member will be required to transfer  
8 or absorb in specified service conditions. Put another way, the cross-sectional size  
9 and wall thickness of the entire length of the structural member is dictated by the  
10 point or points of maximum stress (plus an added safety factor), and the  
11 component is oversized (i.e., contains excess material and strength) elsewhere  
12 along its straight or curvilinear length. Increased wall thickness of a hollow  
13 support member increases the strength of the member (up to an internally solid  
14 structure), but with a resultant increase in the materials needed to produce the  
15 member, and the overall weight of the member. Likewise, the cross-sectional size  
16 can be increased with a resultant increase in materials.

## 17 18 SUMMARY OF THE INVENTION

19 The present invention provides a metal unitary member with a  
20 number of features having parameters that can be varied alone or in combination  
21 with other parameters to customize configuration of the members for a particular  
22 service environment. A unitary structural member of the invention includes a

1 plurality of web portions extending radially from each other and extending with  
2 each other in an axial direction. A plurality of outer portions extend in an axial  
3 direction with the web portions and extend between the web portions in cross-  
4 section. The plurality of outer portions define a radially outer surface of the  
5 member. The axial directions of the web portions and outer portions may be  
6 straight or curvilinear so that the web portions and outer portions may be straight  
7 or curvilinear in trajectory.

8 ~~Preferably, the plurality of web portions extend radially from a~~  
9 ~~substantially central portion that extends in an axial direction with the web~~  
10 ~~portions and the outer portions. The axial direction of the substantially central~~  
11 ~~portion may be straight or curvilinear. The central portion, the plurality of web~~  
12 ~~portions and/or the radially outer portions of the unitary tubular member may have~~  
13 ~~a linear or curvilinear trajectory in a radial direction.~~

14 Preferably, the plurality of web portions includes a plurality of  
15 perforations. The plurality of web portions may vary in radial length at various  
16 axial positions along the member. The outer portions spanning between the web  
17 portions may expand in arc length, and as a result, the unitary tubular member may  
18 vary in cross-sectional size and/or shape. The outer portions preferably are  
19 arched, but may instead be otherwise curvilinear or linear in configuration to form  
20 complex and variable shapes and/or variable sizes of the cross-section of the  
21 member. The web portions may be disposed at substantially equal intervals,  
22 disposed with varying intervals but symmetrically, or disposed at varying intervals

1 to produce an asymmetrical cross-section. By varying the shape and/or length of  
2 the outer portions and the number, configuration, or positioning of the web  
3 portions, a variety of cross-sectional shapes and sizes can be designed and  
4 optimized for particular service conditions.

#### 6 BRIEF DESCRIPTION OF THE DRAWINGS

7 FIG. 1 is an enlarged end view of a unitary structural member according to  
8 one embodiment of the present invention;

9 FIG. 2 is a perspective view of a pair of connected unitary structural  
10 members;

11 FIG. 3 is a cut away view of a unitary structural member according to  
12 another embodiment of the present invention;

13 FIGs. 4A-4D are simplified drawings of unitary structural members varying  
14 in web portion radial length and/or trajectory;

15 FIGs. 5A-5D are simplified drawings of embodiments of the unitary  
16 structural member having varying numbers and configurations of web portions;

17 FIGs. 6A-6D are simplified sketches of unitary structural members having  
18 varying numbers and/or shapes of web portions and/or outer portions;

19 FIG. 7 is a perspective view of a pair of unitary structural members  
20 showing connecting structures;

21 FIG. 8 is an analytical taxonomy of preferred types of processes for  
22 manufacturing complex shaped metal components;

FIG. 9 illustrates computer-aided manufacturing processes, including some for forming unitary structural members of the invention;

FIG. 10 is a chart showing steps in an investment casting process for forming a unitary structural member of the invention;

FIG. 11 is a chart summarizing steps in an investment casting process for manufacturing a prototype unitary structural member;

FIG. 12 is a screen capture of computer models of pattern components for an example embodiment of a unitary structural member;

FIG. 13 is a screen capture showing the internal structure of the unitary structural member;

FIG. 14 shows, in solid and in line drawing, a digital assembly of a pair of unitary structural members;

FIG. 15 shows examples of three-dimensional printing of expendable patterns for manufacturing the unitary structural member;

FIG. 16 shows a pair of pattern components in a "green" state after powder removal;

FIG. 17 shows part patterns for producing a unitary structural member, with gating attached;

FIG. 18 shows a step in an investment casting process for producing unitary structural member;

FIG. 19 shows steps in the investment process following the steps shown in FIG. 18;

1 FIG. 20 shows molds for forming a unitary structural member, drying in  
2 air;

3 FIG. 21 shows a metal pouring operation;

4 FIG. 22 shows solidifying castings in which the metal has been poured;

5 FIG. 23 shows steps in destruction of the ceramic mold shown in FIG. 22;

6 FIG. 24 shows the unitary structural member in its "as cast" state prior to  
7 removal of gating;

8 FIG. 25 shows castings for the unitary structural member after removal of  
9 the portion of the gate;

10 FIG. 26 shows the casting of FIG. 25 after removal of the remainder of the  
11 gating;

12 FIG. 27 shows a grinding process for the casting of FIG. 26;

13 FIG. 28 shows steps in welding together a pair of unitary structural  
14 members;

15 FIG. 29 shows the welded pair of unitary structural members after the  
16 process shown in FIG. 28;

17 FIG. 30 shows the joined unitary structural members of FIG. 29 during a  
18 sandblasting process;

19 FIGs. 31A and 31B show radiographs of the formed unitary structural  
20 member; and

21 FIG. 32 is a diagram showing the process for indirect additive manufacture  
22 of a unitary structural member.

1  
2 DETAILED DESCRIPTION OF THE INVENTION  
3

4 A metal unitary structural member of the invention includes a  
5 plurality of web portions extending radially from one another and extending with  
6 each other in an axial direction, and a plurality of outer portions extending  
7 between the web portions in cross-section. A high strength to weight ratio is  
8 achieved, especially with the use of preferred perforations in the web.  
9 Advantageously, the general invention admits of variations for one or more of the  
10 portions of the unitary tubular member, e.g., the trajectory of the web portions or  
11 outer portions, or the variation of the radial length of the web portions along the  
12 axial length. These and other variations of the general invention permit a designer  
13 to customize various features of the unitary member for particular uses or  
14 operating environments, such as for specific aspects of their intended service  
15 conditions, with a greater flexibility in customization than many conventional  
16 designs. In addition, designers are freed from basing a complete design of a  
17 structural member on its point of maximum stress.

18 Referring now to the drawings, FIG. 1 shows a first, preferred type  
19 of embodiment unitary metal structural member 10 according to the present  
20 invention, and illustrates a number of preferred features. To provide reinforcing  
21 support (stiffness or strength, for example) to the unitary structural member 10,  
22 and to increase the strength-to-weight ratio of the member, a plurality of web  
23 portions 12 are provided, which extend with each other in an axial direction, and

extend radially from each other. The axial direction of the web portions 12 may be linear or curvilinear in trajectory. The web portions 12 may be linear in radial trajectory (as shown in FIG. 1) or curvilinear, as shown by example in FIG. 2 and extend between outer portions 14. Radial, as used herein, indicates a trajectory, whether linear or curvilinear, that originates at the intersection of web portions at any point along an axial extension thereof and extends to an outer portion 14 at any point along an axial extension thereof. In segments, the web portions 12 form an internal reinforcement structure for the unitary structural member 10. The number and radial length and/or shape of included web portions 12 may vary according to, for example, the size and intended service conditions of the particular unitary structural member 10. Preferably, though, the unitary structural member 10 includes at least three web portions 12 for distributing a load applied to the member.

Extending between the plurality of web portions 12 in cross-section, a plurality of outer portions 14 extend around the unitary structural member 10 and in an axial direction with the web portions 12, to define in combination an outer surface 16 of the unitary structural member. The outer surface 16 may be of a complex cross-sectional shape, such as the shape formed by the arched outer portions 14 shown in FIG. 1, or may be, for example, circular or rectilinear in cross-section. The preferred arched configuration for the outer portions 14 further enhances structural integrity of the unitary structural member 10. Loads applied to outer portions of the arched outer portions 14 (lateral loads) in the embodiment



1 shown in FIG. 1 are efficiently directed to and through one or more of plurality of  
2 web portions 12. This preferred type of the unitary structured member 10  
3 improves stiffness of the internal reinforcement for the unitary structural member  
4 and facilitates optimal distribution of lateral loads to the internal plurality of web  
5 portions 12.

6 As shown in FIG. 1, and as more clearly seen in FIG. 2, for example,  
7 the outer surface defined by the arched outer portions may form a corrugated  
8 configuration, with furrows 18 that align with the plurality of web portions. The  
9 extent of the corrugation (furrow 18 depth) may be customized depending upon  
10 component-specific service conditions by varying the radial length of selected web  
11 portions 12 and the shape and/or thickness of selected radially outer portions.

12 In the embodiment shown in FIGs.1 and 2, the web portions 12  
13 extend from one another and from a substantially central (in cross-section) portion  
14 20 at or near the intersection of the web portions 12. The central portion 20 itself  
15 extends axially along the member 10. The central portion 20 may, but not  
16 necessarily, be continuous along its axial direction. The axial direction defined by  
17 the central portion 10, preferably followed substantially in parallel by the  
18 remainder of the unitary structural member 10, including the web portions 12 and  
19 the outer portions 14, may be either lineal or curvilinear in trajectory. FIG. 2, for  
20 example, shows the member, including the central portion 20, extending axially  
21 along a curvilinear trajectory. The central portion 20 shown in FIG. 1 is  
22 substantially circular in cross-section, but in other embodiments, it may have a

1 different cross-sectional shape. One skilled in the art will appreciate that, by  
2 selectively varying the axial trajectory of the central portion 20, web portions 12  
3 and/or the outer portions 14, the overall trajectory of the unitary structural member  
4 10 can be configured to meet particular structural needs. In the radial direction,  
5 the central portion 20 may be symmetrical, or asymmetrical, such as in a spline  
6 trajectory.

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7 The (optional) central portion 20, the plurality of web portions 12,  
8 and the outer portions 14 are preferably integral portions of the unitary structural  
9 member 10. By "unitary", it is intended to mean that the unitary structural  
10 member 10 is formed in a single, integral piece; that is, the unitary structural  
11 member is not a fabrication of separate sections. However, individual unitary  
12 structural members 10 can themselves be sections of a larger combined structure  
13 22, as shown in FIG. 2. In the arrangement shown in FIG. 2, a pair of unitary  
14 structural members 10 having a configuration similar to that shown in FIG. 1, are  
15 connected via mating connective structures 24, one of which is more clearly seen  
16 in FIG. 7. The connective structures 24 may be integrally formed on one or both  
17 ends of the unitary structural members 10. Preferably, the connective structures  
18 24 include a self-registering connector 10; that is a connector 26 configured to  
19 prevent relative rotation of connected members. The self-registering connector 26  
20 may include a male or female connector 28, as shown in FIG. \_\_, a pin or other  
21 independent connection, or another type of connection. To combine a pair of the

1 unitary structural members 10, the connective structures 24 are connected and  
2 preferably adhered, welded or bonded to form the combined structure 22.

3 As further shown in FIG. 1, a plurality of perforations 30 is formed  
4 within the plurality of web portions 12 to form perforated web portions. The  
5 perforations 30 are disposed and arranged to be axially aligned with the plurality  
6 of web portions 12. Though the perforations 30 are not required, the present  
7 inventor has discovered that perforated web portions 12 provide significant  
8 structural integrity with a high strength-to-weight ratio. The perforations 30 also  
9 provide additional ways to customize the unitary structural member 10 by varying,  
10 for example, the configuration and arrangement of the perforations.

11 As shown in FIG. 1, the perforations 30 may be relatively large and  
12 centrally located on the plurality of web portions 12, and may be disposed within  
13 the plurality of web portions radially symmetrically with respect to the central  
14 portion 20. The perforations 30 may also be radially disposed about an  
15 intersection of the web portions 12, as shown in FIG. 3. In this way, the  
16 perforated web portions 12 are conceptually similar to internal surface ribs that  
17 intermittently bridge to their opposing counterparts via the center of a particular  
18 cross-section. If such perforations 30 are part of web portions 12 that extend from  
19 the central portion 20, the perforations create discontinuity of the central portion at  
20 their location. The perforations 30 preferably are axially disposed within the  
21 plurality of web portions 12 along their respective axes. In this way, it will be  
22 appreciated that, as is apparent in FIG. 1, cross-sections of the unitary structural

1 member 10 will vary at least in shape along particular axial positions along the  
2 unitary structural member. For at least this reason, it is also to be understood that,  
3 by describing that the plurality of web portions 12 "axially extend" along the  
4 unitary structural member 10, the cross-sections may vary in shape and/or size  
5 along the various axial portions of the unitary structural member, though the  
6 member may otherwise be of substantially uniform cross-sectional size and shape.

7 The external surfaces 16, whether corrugated, smooth, or otherwise,  
8 may also include perforations (not shown) in order to further optimize strength-to-  
9 weight ratios. The use of external perforations may also be dependent on  
10 anticipated service conditions. Alternatively, the outer surface 16 may be  
11 relatively continuous and/or smooth in profile.

12 The wall thickness of the central portion 20, plurality of web  
13 portions 12, and/or the plurality of outer portions 14 may be either constant or  
14 variable depending on, for example, manufacturing process requirements and the  
15 extent to which the strength-to-weight ratio is optimized. For example, to provide  
16 a relatively smooth, cylindrical outer surface 16 with the arched outer portions 14,  
17 as shown in FIG. 5D, a designer may selectively increase the wall thickness of the  
18 outer portions to fill in the furrows 18.

19 It is an important aspect of the present invention that, among other  
20 things, the cross-sectional size and/or shape, wall thickness, axial trajectory,  
21 component material, and/or arrangement of the unitary structural member 10,  
22 including the perforations 30, can substantially vary as a result of varying the

1 radial size or shape or the trajectory of the central portion 20, plurality of web  
2 portions 12, or plurality of outer portions 14, or selected ones of these portions,  
3 throughout the member, or at axial positions along the member. The variances  
4 contemplated may be present between particular unitary structural members 10, or  
5 within one of the unitary structural members. By selectively varying one or more  
6 of these parameters in the design of the member 10, unique unitary structural  
7 members 10 may be formed that are optimized for specific use environments. The  
8 unitary structural members may vary in, for example, cross-sectional size or shape,  
9 trajectory shape, or number of web portions 12.

10 By varying size and/or shape of one or more of the plurality of web  
11 portions 12, the cross-sectional size and shape of the unitary structural member 10  
12 varies accordingly. The unitary structural members 10 may thus be designed to  
13 have optimum sizes, cross-sectional shapes, or strengths at particular axial  
14 positions to meet particular service conditions. For example, variable service  
15 requirements along the unitary structural member 10 length may result in  
16 optimizations in terms of size, shape, strength, and/or material usage.

17 FIGs. 4A-6D are illustrative examples of embodiments of the unitary  
18 structural member 10, showing effects of varying one or more of the above-  
19 described parameters on embodiments of the unitary structural member. FIGs.  
20 4A-4D illustrate the effect of variations in the radial length of the plurality of web  
21 portions 12 and/or the trajectory of the central portion 20 (and thus the unitary  
22 structural member 10). In FIG. 4A, the radial length of the plurality of web

1 portions 12 varies along axial positions of the unitary structural member 10,  
2 increasing near the axial middle of the member, and decreasing near the ends. The  
3 plurality of outer portions 14 vary in arc length accordingly to extend between the  
4 plurality of web portions 12, so that the unitary structural member 10 maintains a  
5 cross-sectional shape that is substantially similar in proportion. The axial location  
6 of maximum cross-sectional size may be designated to meet particular service  
7 conditions. The axial trajectory of the unitary structural member 10 in FIG. 4A is  
8 curvilinear.

9 By keeping the radial length of the plurality of web portions 12  
10 relatively constant while maintaining the curvilinear trajectory of the central  
11 portion 20, the unitary structural member 10 shown in FIG. 4B can be produced.  
12 FIGs. 4C and 4D show the effect of altering the design of FIGs. 4A and 4B,  
13 respectively, by providing a straight trajectory for the central portion 20.

14 ~~FIGs. 5A-5D illustrate an effect of varying the number of web~~  
15 ~~portions 12, where the plurality of web portions and the arched outer portions are~~  
16 ~~disposed about the central portion 20 in generally equal intervals. FIGs. 5A, 5B,~~  
17 ~~and 5C include three, four, and five web portions 12, respectively. The arched~~  
18 ~~outer portions span between the plurality of web portions 12, forming corrugations~~  
19 ~~in the outer surface 16 of the unitary structural members 10. It will be apparent~~  
20 ~~that as the number of symmetrical web portions 12 increases, the outer surface 16~~  
21 ~~may become more circular in cross-section. FIG. 4D includes eight web portions~~  
22 ~~12, and the wall thickness of the web portions 14 and/or the arched outer portions~~

1 are increased at the circumferential position of the radially outer portions. This  
2 design, as described above, may result in a smooth, continuous outer surface 16, as  
3 shown.

4 FIGS. 6A-6D illustrate an effect of varying the number, length,  
5 and/or direction of the plurality of web portions 12, and also varying the shape of  
6 the radially outer portions 14 spanning the web portions. FIG. 6A shows six web  
7 portions 12 that are disposed unequally about the cross-sectional profile of the  
8 unitary structural member 10. The arched outer portions 14 span to connect the  
9 web portions 12. In FIG. 6B, seven web portions 12 are shown, and the radially  
10 outer portions 14 vary. Some outer portions 14 are arched, and have a greater wall  
11 thickness at the web portions 12 to provide a smooth outer surface 16. Other outer  
12 portions 14, however, are not arched, but are straight, providing a rectilinear side  
13 to the unitary structural member 10. The web portion 12 extends beyond the outer  
14 portion 14 disposed over it to create a T-shape profile 32 at the top (as shown) of  
15 the unitary structural member 10. FIGS. 6C and 6D show variations of the unitary  
16 structural member 10 of FIG. 6B, having five and three cavities, respectively,  
17 without a web portion 12 extending beyond the outer portions 14.

18 FIG. 3 additionally illustrates one example of the central portion 20  
19 being generally curvilinear in cross-section, as opposed to a substantially  
20 cylindrical central portion 20 shown in other embodiments.

21 The perforations 30 within the plurality of web portions 12 may be  
22 disposed symmetrically about the central portion 20, as shown in FIG. 1, or

1 additionally or alternatively may be centered on the plurality of web portions 12 as  
2 shown in FIG. 3, and as described above. In either approach, the size and quantity  
3 of the perforations 30 may vary with cross-sectional dimensions and service  
4 conditions. For example, the perforations 30 may be smaller and/or more  
5 numerous.

6 To manufacture the unitary structural member 10 of the present  
7 invention, particularly types of embodiments that include perforations 30, a  
8 number of methods are disclosed and described below. The description below,  
9 however, is not intended to limit the particular scope of manufacturing methods  
10 contemplated for the unitary structural member 10.

11 FIG. 8 is an analytical taxonomy of preferred types of processes for  
12 manufacturing the metal unitary structural member 10 of the present invention.  
13 As described in the legend of FIG. 8, those manufacturing processes with a  
14 capacity to produce the metal unitary structural member 10 are highlighted in gray  
15 and with a black dot.

16 There are two preferred general categories of manufacturing  
17 processes for producing the metal unitary structural member 10 of the invention.  
18 The metal unitary structural member 10 can be manufactured indirectly using  
19 various types of investment (ceramic mold) casting. The invention can also be  
20 made directly or indirectly using additive metal forming technologies. All  
21 preferred methods of manufacturing the metal unitary structural member 10,  
22 however, typically require three-dimensional data obtained from digital solid



1 models of the invention. These production processes are, therefore, what are  
 2 generally termed computer-aided manufacturing (CAM) processes. A summary of  
 3 preferred fundamental CAM processes for making the metal unitary structural  
 4 member 10 is presented in FIG. 9. Those fundamental manufacturing processes  
 5 with the capacity to produce member 10 with internal features are highlighted with  
 6 a black square in the column to the far right in to FIG. 9.

7           The metal unitary structural member 10 having perforated web  
 8 portions 12 can be investment cast in most alloys from additively or subtractively  
 9 formed expendable patterns. Additively formed patterns are made from digital  
 10 data using commercially-available computer numerically controlled (CNC) layer-  
 11 based solid freeform fabrication technologies and materials suitable for  
 12 combustion or melting. Subtractively-formed patterns are made from digital data  
 13 using commercially-available multi-axis CNC milling machines or routers.  
 14 Depending on the required size of the metal unitary structural member 10, it will  
 15 often be necessary to subdivide the member into segments that can fit within the  
 16 build chamber of a solid freeform fabrication device. These segments can be  
 17 made to self-register with the correct orientation and then simply glued together as  
 18 shown in FIG. 2. Patterns made using subtractive methods will have to be  
 19 subdivided to accommodate otherwise inaccessible internal features (i.e. internal  
 20 perforated webs will necessarily be discreet CNC milling operations). The  
 21 resulting self-registering subtractively formed pattern components are then  
 22 assembled into a complete pattern.

1 In order to make the metal unitary structural member 10 having  
2 perforated web portions 12, it is preferred first to create a digital representation of  
3 it in a parametric solid modeling program that can accommodate and facilitate the  
4 generation of complex geometry. Examples of such software include  
5 Pro/Engineer® by Parametric Technology Corporation, Unigraphics Solutions®  
6 by EDS, and Catia® by Dessault Systemes. It is also preferred to use such  
7 software because it can accommodate the digital assembly of subcomponents  
8 and/or the subdivision of large components into segments small enough to fit in  
9 the build chamber of a particular additive manufacturing process.

10 Once a particular metal unitary structural member 10 has been  
11 digitally modeled, the model is then either directly or indirectly (via data exchange  
12 in a neutral format such as IGES) imported into finite element analysis software  
13 and evaluated per the anticipated structural service conditions. Specific material  
14 properties will then be applied to the model prior to analysis, and this analysis will  
15 further inform and refine the optimization of the component in terms of its  
16 strength-to-weight ratio. In other words, material usage in terms of wall thickness,  
17 web 30 thickness, and the size and configuration of perforations 30 will be  
18 digitally optimized relative to the required strength (plus a safety factor). In most  
19 cases, it is likely that a variety of the perforations 30 for the web portions 12 will  
20 be digitally modeled in advance of analysis, along with a varying quantity of the  
21 web portions. This will make it possible for the analytical results of several  
22 potentially optimal configurations to be compared and assessed. It is most likely

1 that the various web portion 12 and perforation 30 configurations would exist in  
2 the same digital model as either parametric variables or sets of geometric features  
3 that can be turned on and/or off prior to the exportation of data. Digital structural  
4 analysis will also highlight areas of critical stress where there is insufficient  
5 material as well as situations where there is excess material that might be removed  
6 from the model if it is not required for manufacturing reasons.

7 In addition to structural optimization analysis, if the metal unitary  
8 structural member 10 is to be manufactured indirectly using an investment casting  
9 process, data from its digital model will usually be exported to a manufacturing  
10 analysis program that will assist in evaluating castability. Casting analysis  
11 programs (e.g. MAGMASoft®) are used to predict the flow of molten metal and  
12 the solidification process and are therefore are able to anticipate likely casting  
13 defects. In some cases, the extent to which the metal unitary structural member 10  
14 can be optimized will be slightly constrained by the need to accommodate casting  
15 requirements such as directional solidification (ferrous alloys) and thorough  
16 distribution of molten metal in the ceramic mold.

17 Once the results of structural and manufacturing analyses have been  
18 incorporated into the computer model for the metal unitary structural member 10,  
19 and once the member has been segmented or subdivided as necessary to  
20 accommodate a particular pattern manufacturing technology, the data defining  
21 surface geometry is exported in an appropriate format, typically in a neutral file  
22 format. This data is then imported into computer-aided manufacturing (CAM)

software. If pattern components are to be made using a subtractive process, the computer code that will direct the automatic carving of these pattern components out of blocks of material using a CNC milling machine will be generated using a CAM program such as MasterCAM® or SurfCAM®. If pattern components are to be manufactured using an additive material forming process, then the geometric data will be imported into the proprietary CAM software provided by manufacturers of commercial solid freeform fabrication devices. All CAM programs for additive material forming, however, provide the means to orient the component as desired and then subdivide it using a slicing algorithm into very thin horizontal layers of a specified thickness. The layer thickness selected will determine the dimensional accuracy of complex surfaces. Thinner layers result in superior resolution and accuracy, whereas thicker layers will result in a faster build rate.

The metal unitary structural member 10 having perforated web portions 12 can be investment cast from expendable patterns made using a variety of commercially-available layer-based solid freeform fabrication (SFF) technologies. In general, SFF technologies that utilize powdered material are the most suitable for making expendable patterns for investment casting the unitary structural members. This is because these SFF technologies use the surrounding bed of powdered material to temporarily support the pattern during the build process, and because powder supporting the freeform tubular pattern's interior can be easily removed with gravity and air flow. SFF technologies that require and

1 generate insoluble support structures for overhanging features are less suited to the  
2 manufacture of the metal unitary structural member 10 because of the difficulty  
3 and necessity of removing these internal temporary support structures prior to  
4 investment casting.

5           Three-dimensional printing (3DP) and selective laser sintering (SLS)  
6 are the two major powder-based SFF technologies. Three-dimensional printing  
7 technology uses a standard ink-jet print head to deposit a water-based liquid binder  
8 onto a starch (cellulose) powder. This binder is deposited in an area  
9 corresponding to a thin horizontal cross-section of the model. The build chamber  
10 is then lowered per the specified layer thickness, and a roller spreads another layer  
11 of powder before the next section is printed. This process is repeated layer by  
12 layer until the pattern is finished, at which time it is then removed from the build  
13 chamber, dried and infiltrated with wax or resin. 3D printed patterns can be easily  
14 sanded and coated as required for investment casting, and they combust without  
15 leaving significant residual ash in the ceramic mold. One type of commercial 3DP  
16 devices that can produce combustible patterns investment casting is manufactured  
17 by Z Corporation and marketed as concept modelers because it has a relatively fast  
18 build rate and slightly less precision than many other commercially available SFF  
19 technologies. For many applications of the metal unitary structural member 10,  
20 however, the accuracy of the process is suitable or can be circumvented by CNC  
21 machining connective interfaces between members.

1 Selective laser sintering technology was developed at the University  
 2 of Texas and commercialized by DTM Corporation in Austin. EOS Gbmh in  
 3 Germany also developed SLS and both companies manufacture their own range of  
 4 machines. SLS is very versatile and can process a variety of materials including  
 5 polymer powders, sand, and metal powders. SLS uses laser heat to raise the  
 6 temperature of powdered polymers (or the binder that coats grains of sand or  
 7 metal) to the point where individual grains fuse together. As with 3DP, SLS parts  
 8 are supported by surrounding powder while being built layer by layer. Both DTM  
 9 Corporation and EOS Gbmh produce materials designed for use in foundries. SLS  
 10 produces very dimensionally accurate expendable patterns.

11 Exceptionally accurate wax patterns for casting very small metal  
 12 unitary structural members 10 having perforated web portions 12 can be made  
 13 using the ModelMaker™ liquid-to-solid inkjet printers manufactured by Sanders  
 14 Prototype, Inc. While this technology automatically generates temporary support  
 15 structures for overhanging features, these supports are built out of a different  
 16 material that can be dissolved with a solvent that will not damage the pattern per  
 17 se. In other words, the support structures for the perforated web portions 12 can  
 18 be removed even though they are physically inaccessible.

19 Fused deposition modeling (FDM) is a SFF technology that uses a  
 20 computer controlled extrusion head to incrementally deposit layers of melted  
 21 thermoplastic materials. FDM machines are manufactured by Stratasys® Inc. and  
 22 the company produces a wax material designed for use in making expendable

1 patterns. Like the other thermoplastic materials available for FDM, this foundry  
2 wax solidifies immediately after being deposited. Water soluble temporary  
3 support materials for FDM have been developed for use with ABS, but liquid-  
4 based support structure removal is not currently available for the foundry wax  
5 used with FDM. This means that FDM is significantly less useful for making  
6 patterns for casting the metal unitary structural member 10 having perforated web  
7 portions 12.

8 While very accurate, stereolithography is another SFF technology  
9 that generates temporary internal support structures that are problematic for  
10 making the metal unitary structural member 10 having perforated web portions 12.  
11 Stereolithography machines are manufactured by 3D Systems and their build  
12 chamber is a vat of ultraviolet-sensitive liquid polymer. The application of laser  
13 light solidifies the liquid polymer layer by layer from the bottom up until a  
14 component is completely built. In order to use this technology to create  
15 expendable patterns, proprietary QuickCast™ software currently must be used.  
16 This software generates a honeycomb structure within the wall thickness of a  
17 pattern, and this internal configuration enables the pattern to collapse inward  
18 during combustion without applying destructive forces to the ceramic mold.  
19 QuickCast™ patterns have been used successfully commercially, but they can be  
20 problematic, and extensive foundry experience is generally required to assure a  
21 reasonable likelihood of success. The difficulty of using stereolithography to  
22 create expendable patterns combined with the likely impossibility of being able to









inches in diameter, although the model can be easily parametrically modified so that these cross-sectional dimensions can vary greatly per service conditions and optimization analysis. The spline or curved trajectory of this particular member 10 lies in a plane, thereby making this tube symmetrical. The web portions 12, their perforations 30, the outer surface 14 (corrugated), and the openings at the connective structure 24 can also be parametrically modified in size and shape in order to facilitate shape and structural optimization. The connective structure 24 between what would otherwise be two 68-inch long members was incorporated into this prototype in order to evaluate and verify one possible design of such a connection. Images of the pattern component computer models are shown in FIGs. 12 and 13, and screen captures of digitally assembled patterns are shown in FIG. 14.

As is shown in FIG. 15, expendable patterns for the prototype metal unitary structural member 10 were three-dimensionally printed on a Z Corporation Z402 3D Printer. Two of these pattern components are shown in their “green” state after powder removal in FIG. 16. Each pattern component was infiltrated with resin in order to obtain sufficient strength for handling and assembly in the foundry, as well as to facilitate further finishing of the external surfaces for aesthetic reasons.

The patterns of a component per se are referred to as the part patterns in ceramic mold casting processes. Complete patterns ready for investment feature gates, runners and other elements that have been attached to the

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1 part pattern in order to facilitate the distribution of molten metal and defect-free  
2 solidification. These features are generally made out of stock prefabricated wax  
3 components and are assembled by hand with foundry glue. These features are  
4 generally collectively referred to as the gating. The part patterns for the prototype  
5 metal unitary structural member 10 having perforated web portions 12 are shown  
6 with their gating attached in FIG. 17.

7           The completed patterns were hand dipped into a variety of slurry and  
8 stucco compositions. Slurry and stucco mixtures are typically engineered for  
9 initial, intermediate, and later coats so that ceramic molds are produced with  
10 excellent cavity wall accuracy, adequate strength, and sufficient permeability. It is  
11 most preferable that the first coat be made using fine silica and bonding agents that  
12 will ensure very accurate replication of pattern surfaces and details. It is equally  
13 preferred that the ceramic shell itself be strong enough to endure handling and the  
14 forces applied during casting, but not so thick that it resists contraction forces  
15 during solidification, which can cause hot tearing. For the prototype metal unitary  
16 structural member, six coats of slurry and stucco were applied and the ceramic  
17 shells were approximately ¼ inch thick. Photographs of the investment process  
18 are shown in FIGs. 18-19, and FIG.20 shows a pattern air drying after the initial  
19 coat of slurry and stucco.

20           Once the final slurry and stucco applications were completely dry,  
21 the invested patterns were melted and burned out in an autoclave at a temperature  
22 of approximately 1650°F. After the resulting ceramic molds had cooled, they were

1 carefully inspected. No defects or cracks were observed and no residual ash was  
 2 found in the cavity. The resulting ceramic molds were then fired in a furnace to a  
 3 temperature of 1200°F immediately before metal casting. The specified 356  
 4 Aluminum was cast at a molten temperature of 1275°F.

5 As is normal for investment casting, the fired molds were carried  
 6 from the furnace using tongs and heat resistant gloves. They were then carefully  
 7 positioned on sand that had been spread on the floor. Molten aluminum was hand  
 8 ladled into the molds, and they were each filled in a matter of minutes. The metal  
 9 pouring operation is shown in FIG. 21.

10 As can be seen in FIG. 22, the solidifying castings began to fracture  
 11 the ceramic molds. Most of the external shell for both castings was easily  
 12 removed by hand and/or with a rubber mallet. The destruction of the ceramic  
 13 molds is shown in FIG. 23. A component for the prototype is shown in its 'as  
 14 cast' state prior to the removal of gating in FIG. 24.

15 An important aspect of the design of the metal unitary structural  
 16 member 10 having perforated web portions 12 is that there is synergy between  
 17 their unique optimizing features, those required to post-process additively-formed  
 18 patterns for casting such members, the features necessary for ceramic mold  
 19 integrity, and the features required to process the invention once it has been  
 20 investment cast. The need to remove mold or support material from the cavity  
 21 after an additively-formed pattern is completed and a casting has solidified  
 22 requires sufficiently-sized openings in the member's 10 ends. The position of

1 these openings at the ends of the members 10 is also optimal in terms of investing  
2 the pattern with slurry (which has to drain well from cavities after dipping), air  
3 drying each coat, and creating structural bridges between cavity molds and the  
4 outer ceramic shell. The perforation of internal webs creates exceptional ceramic  
5 mold strength and integrity. In other words, the optimizing features of the metal  
6 unitary structural members also significantly enable their indirect manufacture  
7 using investment casting.

8 The castings for the prototype metal unitary structural member 10  
9 having perforated web portions 12 are shown with some of their gating cut off in  
10 FIG. 25. Initial removal of the gating was done with a band saw, and this  
11 operation left about  $\frac{1}{4}$  inch of each gate on the surface of the castings. Most of  
12 this was removed using belt grinding machines, and the results of this process are  
13 shown in FIG. 26. Each of the gate locations was then carefully blended using  
14 hand held grinding devices as shown in FIG. 27. Evidence of surface grinds  
15 quickly and completely disappeared after the castings were sand blasted, although  
16 this was not done until after the two parts had been welded together.

17 In order to be able to present the connection in this prototype in both  
18 a welded and a non-welded state, the decision was made to weld two-thirds of the  
19 circumference of the joint. The components for the prototype metal unitary  
20 structural member having perforated web portions are shown being welded  
21 together in FIG. \_\_. The slight discoloration of the welded joint visible in FIG. 29  
22 (left) is the result of an immersion heat treatment.

1 Prior to the specified heat treatments, the prototype metal unitary  
 2 structural member 10 was sand blasted to provide consistent surface texture and  
 3 ensure that the gates and weld had been thoroughly blended with adjacent surfaces  
 4 (i.e. it is difficult to verify surface accuracy because of the markings created  
 5 during grinding). Photographs of the welded castings during the sand blasting  
 6 process are shown in FIG. 30.

7 Two heat treatments processes that are typically specified for  
 8 structural aluminum components and are normally used in conjunction with each  
 9 other were applied to the prototype metal unitary structural member 10. The first  
 10 heat treatment process is the T-4 heat treatment, and it involves immersing  
 11 castings for 24 hours in liquid (mostly water) that is heated to a temperature 100°F  
 12 less than the melting point of the alloy (in this case, therefore, 1175°F). This  
 13 process permits much more controlled solidification of a casting and results in a  
 14 higher degree of homogenization among the various alloying ingredients. When a  
 15 casting is removed from a T-4 heat treatment, it is immediately quenched to  
 16 'freeze' the metal in this improved state. The second heat treatment is air-based  
 17 rather than water-based, and is known as the T-6 process. This process involves  
 18 placing a casting in a furnace and heating it to a temperature between 300°F and  
 19 350°F for a few hours to artificially harden the metal and increase its strength.  
 20 The duration of a T-6 heat treatment is usually a few hours, but the precise time is  
 21 determined by the foundry based on experience and the part's geometry.

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1 Prior to the castings being welded together, they were inspected  
2 visually and using both dye-penetrant and radiographic techniques. Visual and  
3 dye-penetrant inspection showed no surface defects, and x-rays indicated that the  
4 castings were sound throughout. In fact, both castings easily met the standards of  
5 ASTM E155 for structural aluminum castings and what is referred to as '3T  
6 sensitivity', which is a standard required of high performance castings for the  
7 aerospace industry.

8 Radiographs of castings that are to be evaluated per ASTM and other  
9 standards include a series of slides with three tiny but different sized holes in  
10 them. (These slides may be purchased from the American Society for Testing and  
11 Materials (ASTM).) Each slide corresponds to a specific casting wall thickness,  
12 and because most castings have more than one wall thickness, several different  
13 slides are usually required for a given radiograph. The tiny holes in each of these  
14 slides are sized relative to a specific casting wall thickness, and they serve to  
15 control the interpretation or 'reading' of a radiograph. If these holes are visible on  
16 a radiograph, then that means that voids or inclusions in the casting corresponding  
17 to the sizes of these holes would also be visible in the radiograph. Because each  
18 of these tiny holes has a different diameter or, more loosely, 'thickness', standards  
19 are specified based on the number of holes that are visible. The term 'thickness' is  
20 generally abbreviated with the letter 'T', and readability standards are therefore  
21 specified as '1-T', '2-T' and '3-T'. Most aluminum castings are required to meet  
22 2-T standards, but many small commercial castings are only required to meet 1-T



1 standards. The aerospace industry, NASA, and other businesses making products  
2 with stringent performance specifications typically demand 3-T certification. Two  
3 radiographs of the metal unitary structural member having perforated web portions  
4 are shown in FIGs. 31 A and B. Both of these castings met '3-T' standards.

5 As described above, in addition to indirect investment casting  
6 methods, the present invention contemplates manufacturing the metal unitary  
7 structural members 10 using direct methods. The metal unitary structural member  
8 10 having perforated web portions 12 can be directly manufactured using various  
9 laser and metal powder based freeform fabrication technologies. These processes  
10 use lasers (or sometimes heat from another energy source) to bond metal powders  
11 that are delivered through nozzles to the heat source. These methods can be  
12 described as layer-based multi-axis CNC metal deposition or welding. Examples  
13 of these processes are discussed below.

14 The metal unitary structural member 10 having perforated web  
15 portions 12 can also be semi-directly manufactured using other metal powder-  
16 based solid freeform fabrication (SFF) technologies, namely three-dimensional  
17 printing (3DP) and selective laser sintering (SLS).

18 These processes can be considered semi-direct methods of  
19 manufacturing metal components because they initially result in skeletal or porous  
20 (approximately sixty-percent dense) products that then must be infiltrated with  
21 molten metal (typically bronze) to create fully dense parts. At present, these  
22 methods, like investment casting, result in material properties that may not be

1 sufficient for some service conditions. However, the companies that manufacture  
2 SLS machines that can process metal powders, DTM Corporation and EOS GmbH,  
3 are developing improved materials and processing techniques in an effort to  
4 minimize this issue. Extrudehone's ProMetal® Division, which manufactures  
5 three-dimensional printing machines specifically for processing metal powders, is  
6 also developing improved materials and processes. It is possible that the metal  
7 products of SLS and 3DP machines will eventually be able to better capture the  
8 strength to weight ratio advantages of the metal unitary structural members 10.  
9 Process diagrams for the indirect additive manufacture of metal components using  
10 SLS and 3DP are shown in FIG. 32.

11           Selective laser sintering processes use a carbon dioxide laser to  
12 sinter and thereby bond powdered materials. A thin layer of powdered material is  
13 spread over a build piston that is lowered incrementally after each layer has been  
14 sintered. Each sintered layer represents a horizontal section through the part.  
15 Layer thickness controls the accuracy or resolution of the part being built. SLS  
16 was first developed for application using powdered polymers, which are readily  
17 bonded by the application of heat, but, from a material standpoint, the process is  
18 more flexible than most solid freeform fabrication technologies because polymeric  
19 binders can be easily added or applied to ceramic or metal powders. Varieties of  
20 metal powders that have been coated with polymeric binders are commercially  
21 available. SLS machines have build chambers that are approximately 15" by 13"  
22 by 18" high.

1           After an entire part has been sintered, it is removed from the powder  
2 and considered to be in a green state. The polymer remaining in green parts is  
3 then burned off in a reducing atmosphere furnace, leaving a stainless steel skeleton  
4 that is about sixty percent dense. This initial heat treatment also further sinters the  
5 metal. Bronze is infiltrated into the steel skeleton in a second heat treatment,  
6 creating a part that is fully dense. Metal parts semi-directly manufactured using  
7 SLS have a strength and hardness superior to aluminum. Their modulus of  
8 elasticity and coefficient of thermal expansion are similar to steel, and they can be  
9 easily machined, welded and finished.

10           A three dimensional printing (3DP) process was invented at MIT  
11 and is licensed to several companies. Each of these businesses is developing  
12 different material technologies. The ProMetal® Division of Extrude Hone  
13 Corporation in Pennsylvania has commercialized the use of metal powders to  
14 make tools and components using 3DP. They manufacture a line of solid freeform  
15 fabrication devices commercially named ProMetal® machines. These machines  
16 have build volumes ranging from 12" by 12" by 10" high to 20" by 36" by 12"  
17 high.

18           ProMetal® machines print a polymeric binder onto layers of  
19 powdered stainless steel or tool steel using an ink jet printhead that deposits  
20 320,000 droplets per second. As with SLS, and as indicated in FIG. 32, this  
21 produces a green part in a bed of loose powder. The remaining polymeric binder  
22 is then burned out in a furnace in a process that also lightly sinters the part. A

1 second heat treatment is used to infiltrate the steel skeleton with molten bronze or  
2 a copper alloy, creating a fully dense part. Completed parts are approximately  
3 sixty percent steel and forty percent bronze (or copper) and these steel/bronze  
4 parts have sufficient material properties for some structural applications. Three  
5 dimensionally printed metal parts can be machined, welded and finished as if they  
6 were stainless steel parts made using other manufacturing processes.

7           Embodiments of the metal unitary structural member 10 having  
8 perforated web portions 12 may be directly manufactured using solid freeform  
9 fabrication technologies that are generally referred to as layer-based metal  
10 deposition processes. Various names have been given to specific direct metal  
11 freeform manufacturing technologies by those organizations developing or  
12 commercializing these processes, and these include laser-engineered net shaping  
13 (LENS<sup>TM</sup>), direct metal deposition (DMD<sup>TM</sup>), and laser additive manufacturing  
14 (LAM<sup>TM</sup>). All of these processes use nozzles to deliver metal powder or wire to a  
15 focused heat source, usually a laser but sometimes another energy source. The  
16 nozzles and heat source collectively comprise what is known as the deposition  
17 head, and these assemblies are typically manipulated in at least three axes using  
18 computer numerical control (CNC) software. In a process very similar to welding,  
19 the heat source melts the powder or wire resulting in a small but controllable  
20 molten pool that quickly solidifies and bonds with the layer below as the  
21 deposition head follows a predetermined computer numerically controlled layer-  
22 specific path. As with the majority of solid freeform fabrication technologies,



1 process. In many instances, the better solution to the present geometric limitations  
 2 of direct metal deposition processes will be to develop six-axis manipulation that  
 3 can accurately and predictably deposit metal from any orientation, and to  
 4 supplement this capacity with path planning software that can successfully  
 5 sequence the deposition of metal so that unbuilt portions of features do not  
 6 become inaccessible during the build process. Process is currently being made on  
 7 developing such solutions to the current geometric limitations of laser and metal  
 8 powder based direct manufacturing processes.

9           Commercially available machines manufactured by Optomec, Inc.  
 10 (LENST<sup>TM</sup>) and Precision Optical Manufacturing (POM), for example, are capable  
 11 of manufacturing some smaller scale applications of the metal unitary structural  
 12 members. It is contemplated that further development and application of gantry-  
 13 based delivery mechanisms and robotically manipulated multi-axis deposition of  
 14 metal at an equal rate from the top, sides, or bottom of a component, in machines  
 15 such as fully-functioning direct metal deposition machines currently being  
 16 developed by Lockheed Martin Aeronautics Company, may be used to  
 17 manufacture the metal unitary structural member 10 having perforated web  
 18 portions 12 using direct metal manufacturing processes.

19           A number of embodiments of the invention, the metal unitary  
 20 structural member 10 have thus been shown and described, having at least the  
 21 several advantages described above. A number of methods have also been shown

1 and described for producing various types of embodiments of the metal unitary  
2 structural member 10.

3 While various embodiments of the present invention have been  
4 shown and described, it should be understood that other modifications,  
5 substitutions, and alternatives are apparent to one of ordinary skill in the art. Such  
6 modifications, substitutions and alternatives can be made without departing from  
7 the spirit and scope of the invention, which should be determined from the  
8 appended claims.

9 Various features of the invention are set forth in the appended  
10 claims.

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